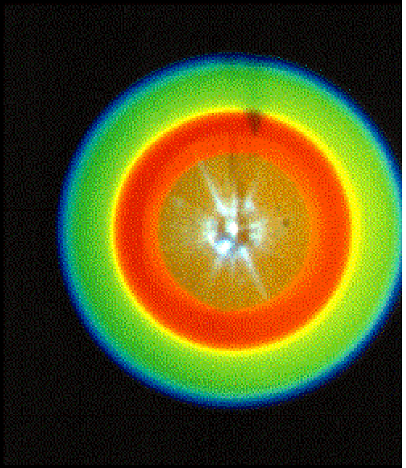
Two Photon Metrology - Getting Down to Business



A. Migdall
Optical Technology Division, NIST

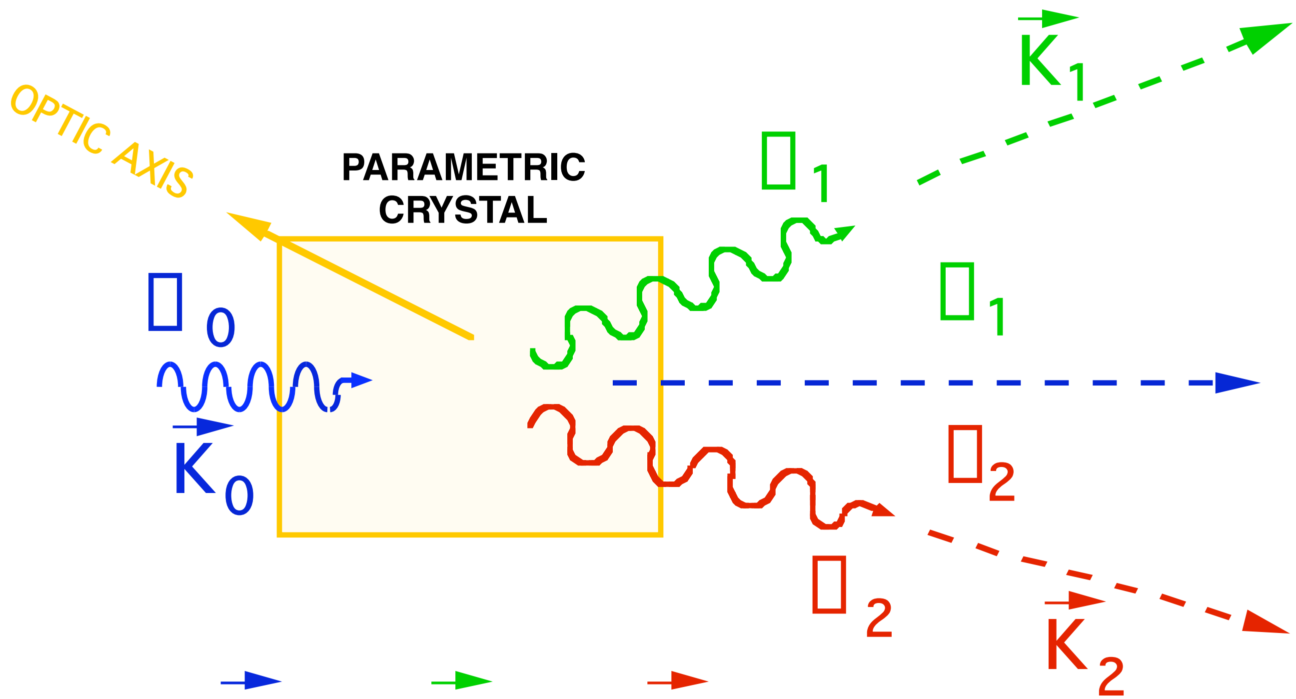
NIST	M. Ware
IEN (Italy)	S. Castelletto, M. Rastello, C. Novera, G.Brida,…
U of Ill	D. Branning
MIT	E. Dauler
BU	G. Jaeger, A. Sergienko, A. Muller
SupOptique (France)	N. Boeuf, I. Chaperot, S. Thomas, R. Tessieres
UMBC	T. Pittman, J. Orszak, Y. H. Shih

Heralded Photons & Metrology

History

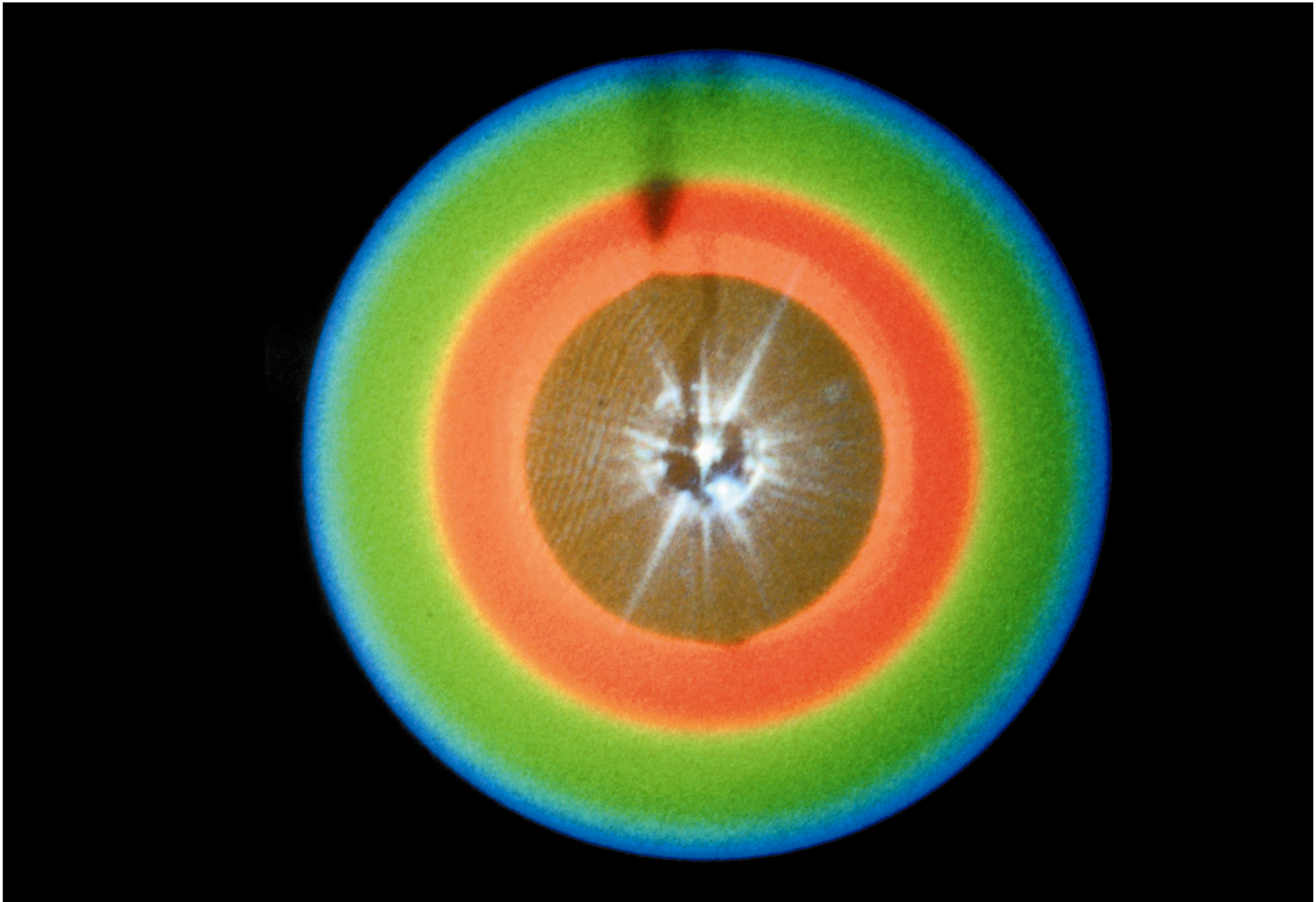
Optical Parametric Downconversion

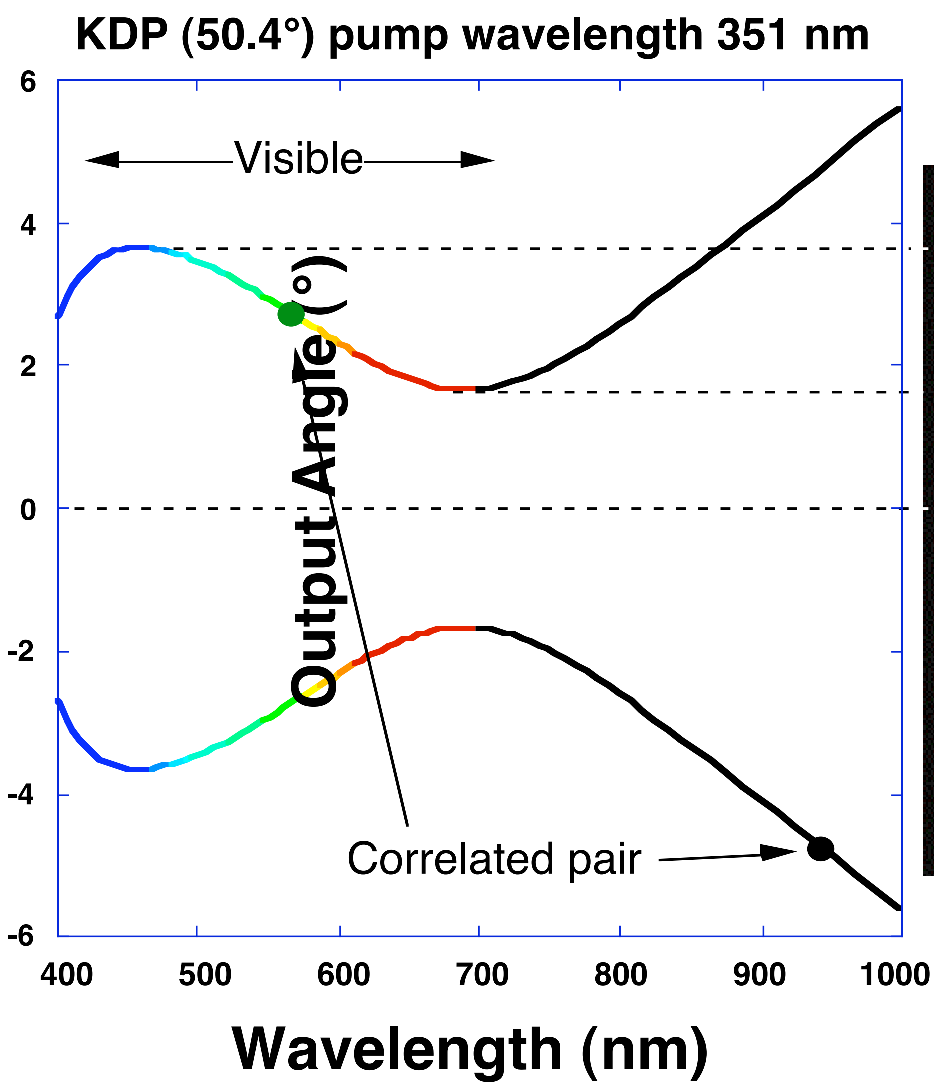
One in - two out

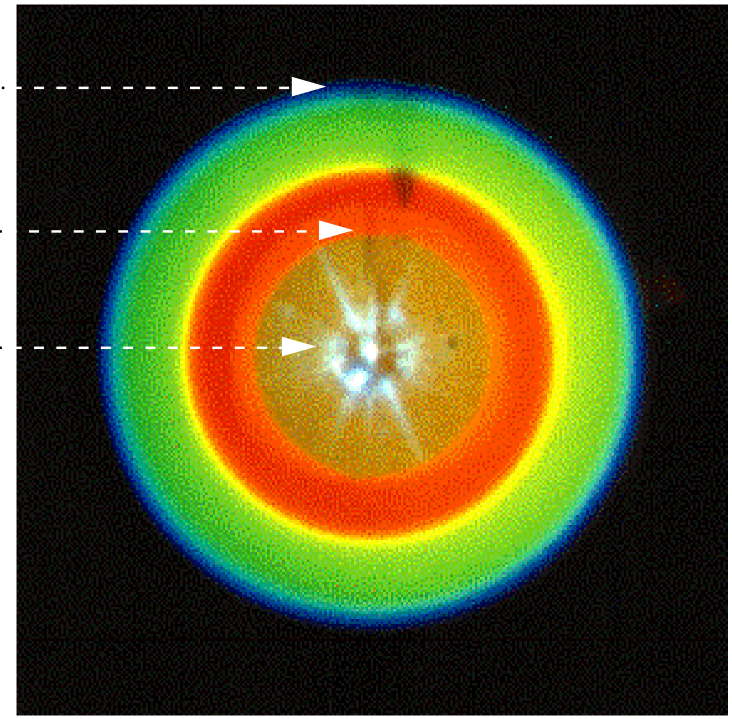


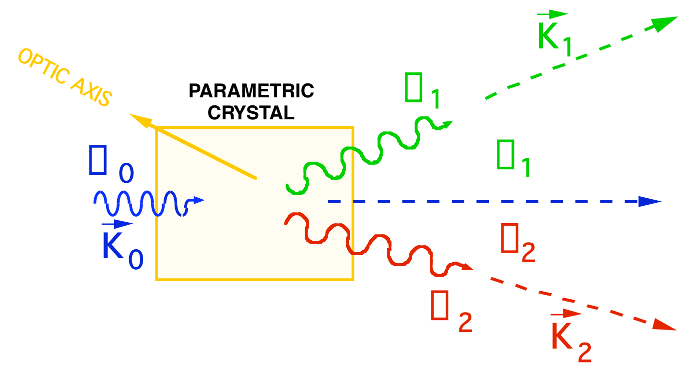
$$\vec{K}_0 = \vec{K}_1 + \vec{K}_2$$

$$□_0 = □_1 + □_2$$





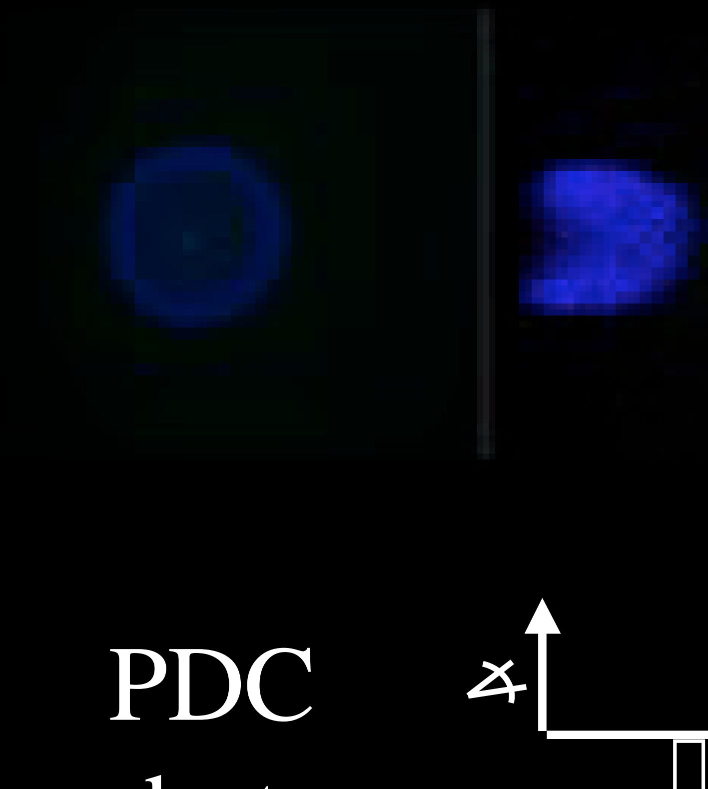




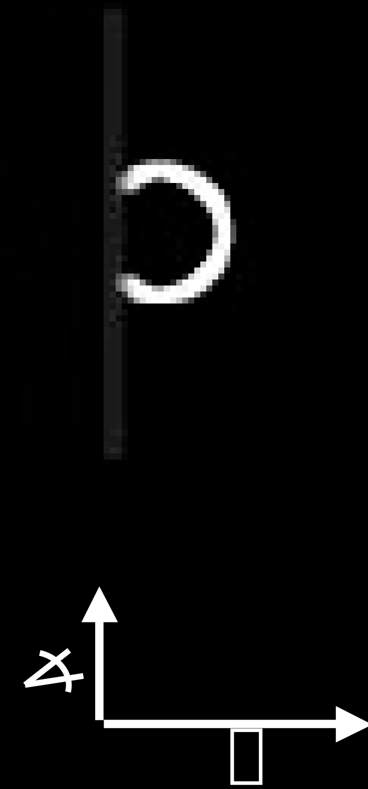
$$\vec{K}_0 = \vec{K}_1 + \vec{K}_2 \qquad \omega_0 = \omega_1 + \omega_2$$

PDC photos as Crystal Optic Axis Tilts

PDC displaying its own phase matching curve

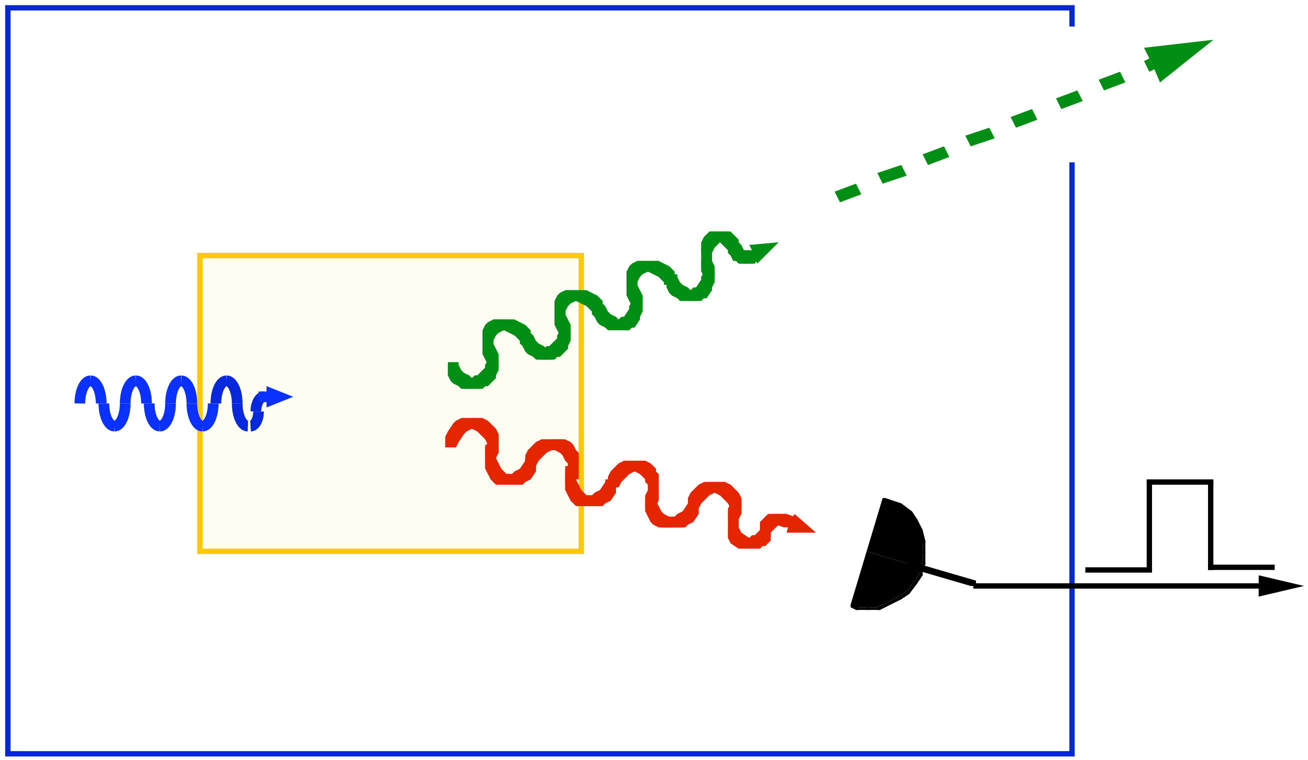


PDC photo



Calc.

Heralded Photon Absolute Light Source



Output characteristics :

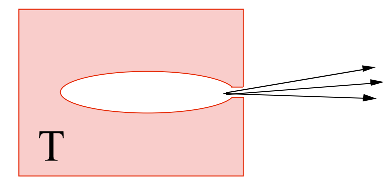
photon #	**➔ known**
photon timing	**➔ known**
wavelength	**➔ known**
direction	**➔ known**
polarization	**➔ known**

We know Metrology has a long an distinguished history and family but,

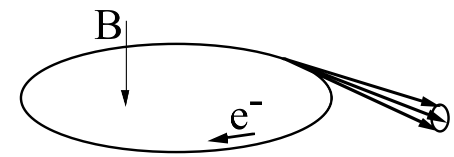
how special is a Heralded Photon Source?

Absolute Radiometric Source Standards

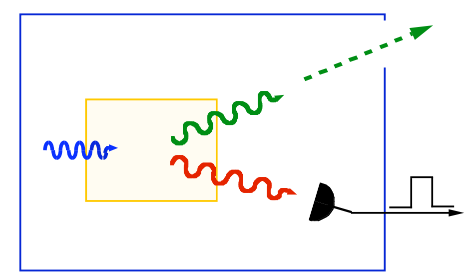
Black Body



Synchrotron



Heralded Photon Source

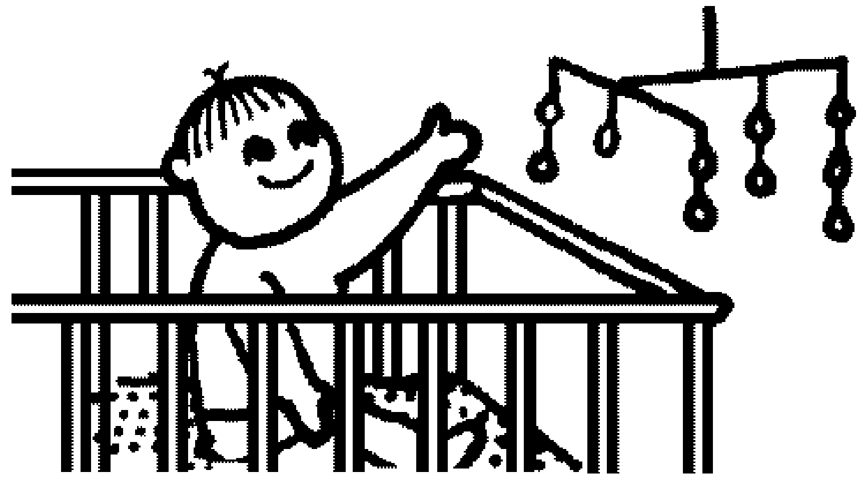


How special is a Heralded Photon Source?

Very special!

Heralded Photons & Metrology

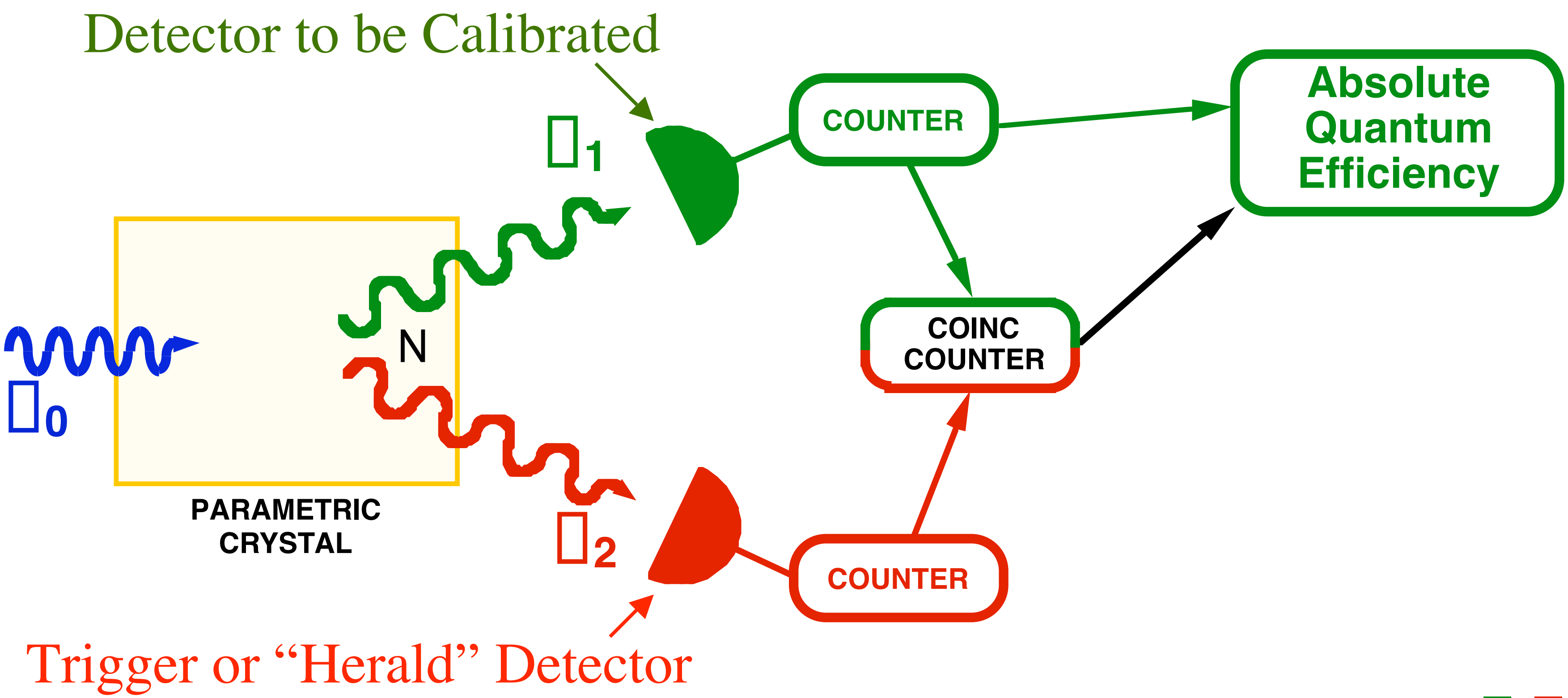
Announce



Absolute Quantum Efficiency

Detector Quantum Efficiency Scheme

No External Standards Needed!



$N_1 = □_1 N$ $N_2 = □_2 N$ $N_C = □_1 □_2 N$

$$□_1 = N_C / N_2$$

Abridged History of Correlated Photon QE Technique:

1910 Particles two-at-a-time for calibration begins - 2□ decay - Geiger & Marsden

1924- Single scintillation seen by two viewers, human observer calibration - Geiger and Werner

1940- Correlated □-□cascade fluorescence, detector calibration - Dunworth

1955- 2 photon cascade source proposed - Brannen, et al. (U of W Ontario)

1961- Predicted spontaneous fluorescence - Louisell, Yariv, Seigman (Bell Labs& Stanford)

1970- First observation of correlation & first detector calibration! -
Burnham and Weinberg (NASA)

1977- Proposal for quantum efficiency application??
Proposal for "Optical Brightness Standard" - Klyshko

Calibrating Human Photon Counters

Effect of Tonic Drug.

It is known that under normal conditions the sensitivity of the human organism to external influences is not the greatest possible. The nerve impulses meet on their way to the brain certain resistances. There are, however, conditions when these resistances are partially removed and all the senses attain special sharpness. For example, 24 hours' starvation produces an increase in sensitivity. The same effect can be obtained more conveniently, however, by the injection or consumption of some "tonic" drug. It was interesting to see if a trained observer could improve his flash-sensitivity in such a way, or if the training itself consisted in diminishing the resistances mentioned. For this purpose a dose of strychnine (1/15 of a grain) was taken by an observer 1 hour before the experiment began. The results obtained showed that the limit was considerably lowered—to about 12 quanta. It must be mentioned, however, that only one such experiment was carried out and the result obtained is therefore not very reliable.

"Some Experiments Concerning the Counting of Scintillations Produced by Alpha Particles"
Chariton and Lea, Cavendish Lab., Proc. Roy. Soc. **122** 304 (1929)

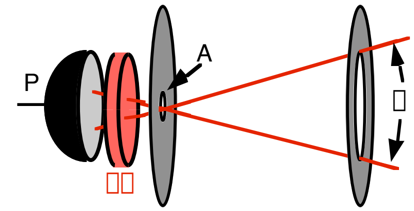
Heralded Photons & Metrology

Announce

Absolute Spectral Radiance

Correlated Photons for Absolute Spectral Radiance

$$\frac{\textbf{Power}}{\textbf{Area x Solid Angle x Bandwidth}}$$



measures *IR* radiance-

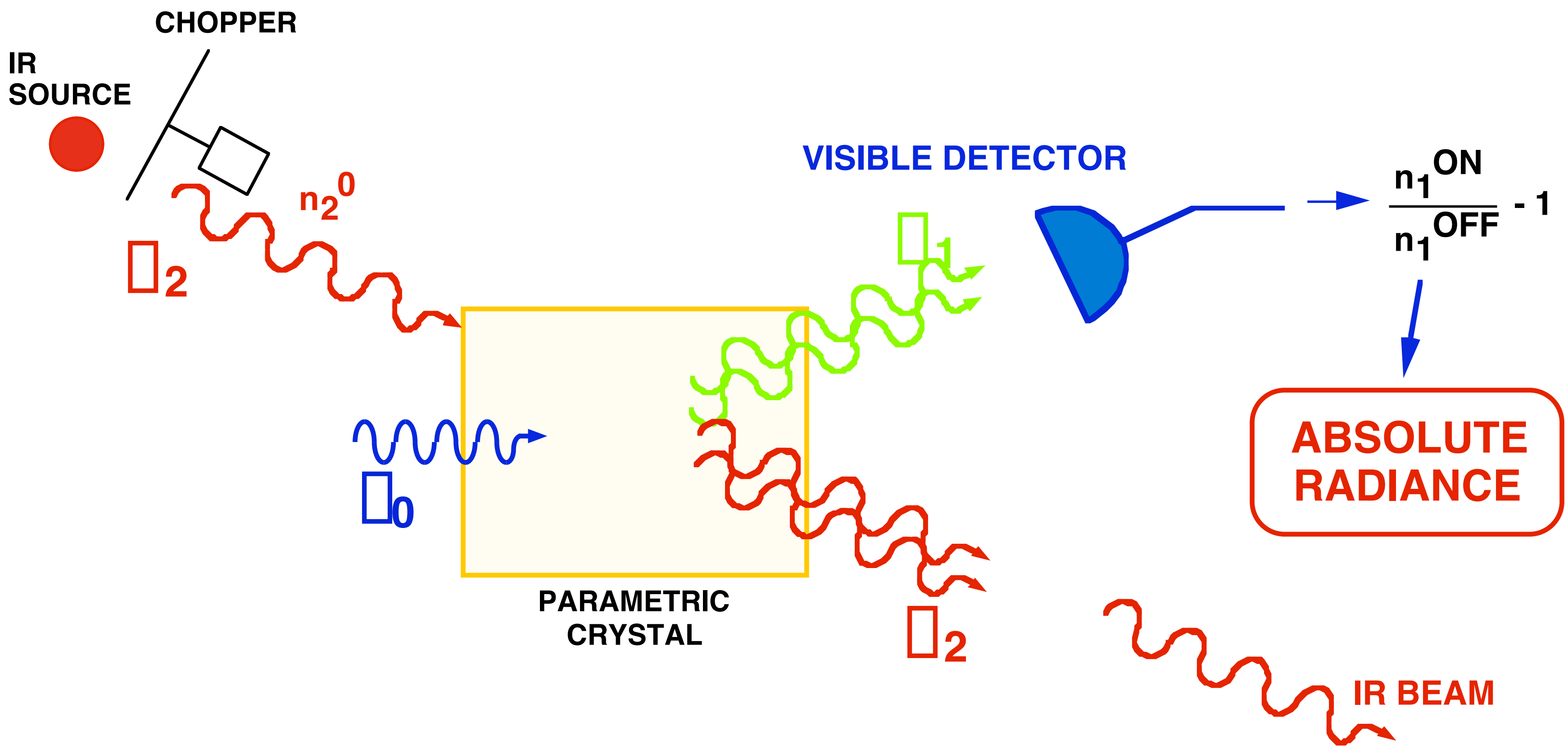
with a *visible* detector & *visible* optics

only method to *directly* measure radiance

>>> New Absolute Radiance Source

Proposed by D. Klyshko '77
Demonstrated by A. Penin '79
Verified at λ=5 μm to ~1% by NIST '98

Absolute Spectral Radiance Method



$n_1^{OFF} = G * 1$ $\qquad$ $n_1^{ON} = G * (1+n_2^0)$

FUNDAMENTAL RADIANCE UNIT $\equiv$ 1 photon/mode $= B_{vac} = hc^2/\lambda^5$

Proposed by Klyshko ‘77
Demonstrated by Kitaeva, et al ‘79

Other children

Ellipsometry
Polarimetry
Tomography
Microscopy
PMD
Clock?

…

Demonstrated but,
is it true metrology?

Getting down to business

Getting down to business - Requirements real metrology–

You say you got it right, but how can you be sure???

- **Measurement protocol**
  - **Internal self consistency tests to verify correct operation**
    - **Does the result depend on parameters as expected?**
    - **Is setup really understood?**

- **External tests**
  - **Intra-lab comparisons: correlated/conventional**
    - **Requires range where both methods work well**
    - **Least accurate method limits comparison**
  - **Inter-lab comparisons: correlated/correlated**
    - **Different measurement setups (e.g. different PDC crystals)**

- **Suitable sample detector (photon counting)**
  - **Stability of – efficiency, dark counts, thresholds, electronics, …**
  - **spatial uniformity**
  - **spectrally smooth response**
  - **Convenience, portability**

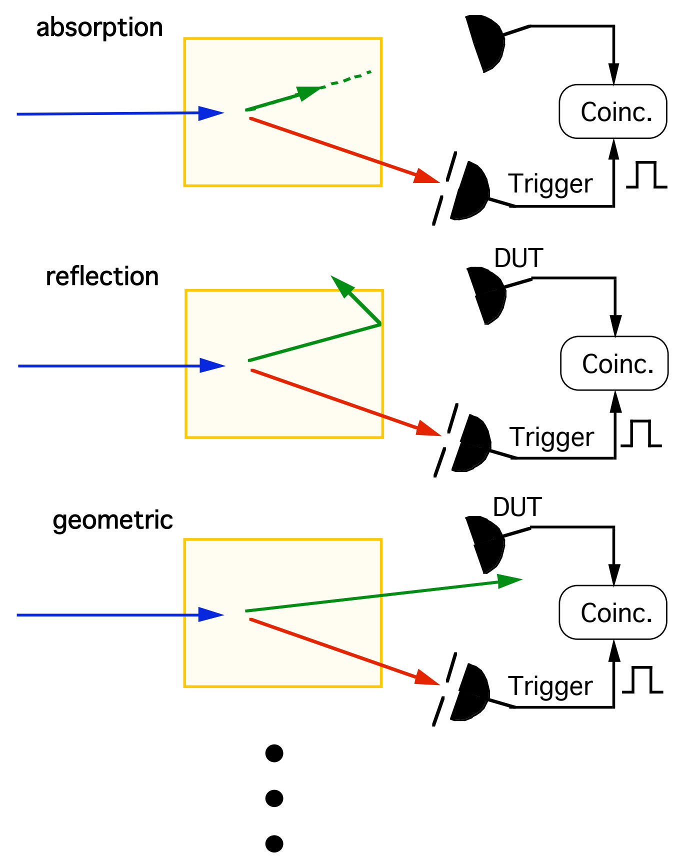
Measurement protocol- internal tests

Verify certainty of collection of photons correlated to trigger

- DUT Optical path transmittance losses (crystal)
  - Calculations & Measurements (possibly in situ)
- DUT Collection Efficiencies
  - Spatial
  - Angular
  - Spectral
  - Electronic

Verify certainty of trigger count rate

- Trigger Backgrounds
  - Dark counts
  - Scattered light



Proposed Protocol (for Quantum Efficiency Measurements)

Philosophy:

Design for minimum losses

Verify uncertainties of what's left

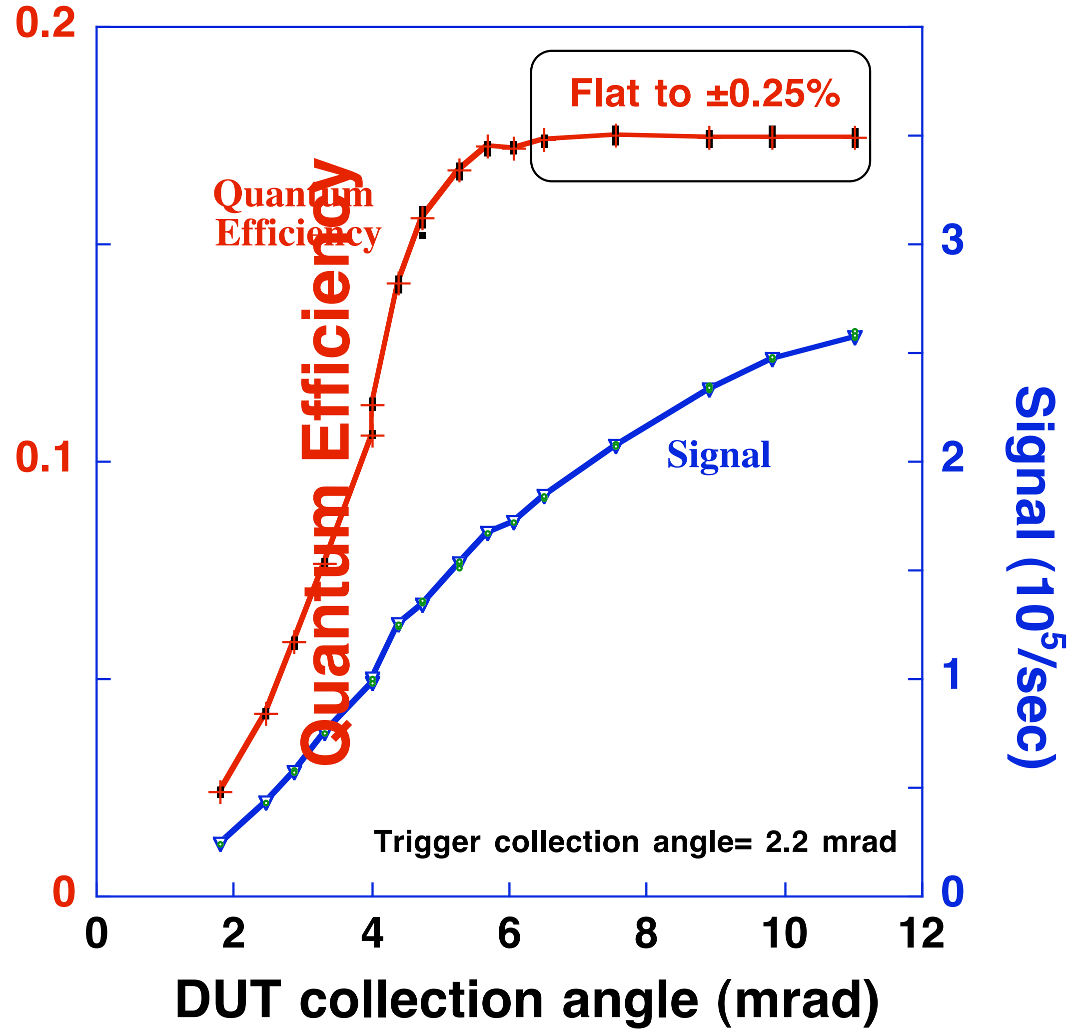
Optical System Design

- Minimize crystal losses
- Minimize crystal-beam interaction region
- Minimize angular spreading of correlated photons

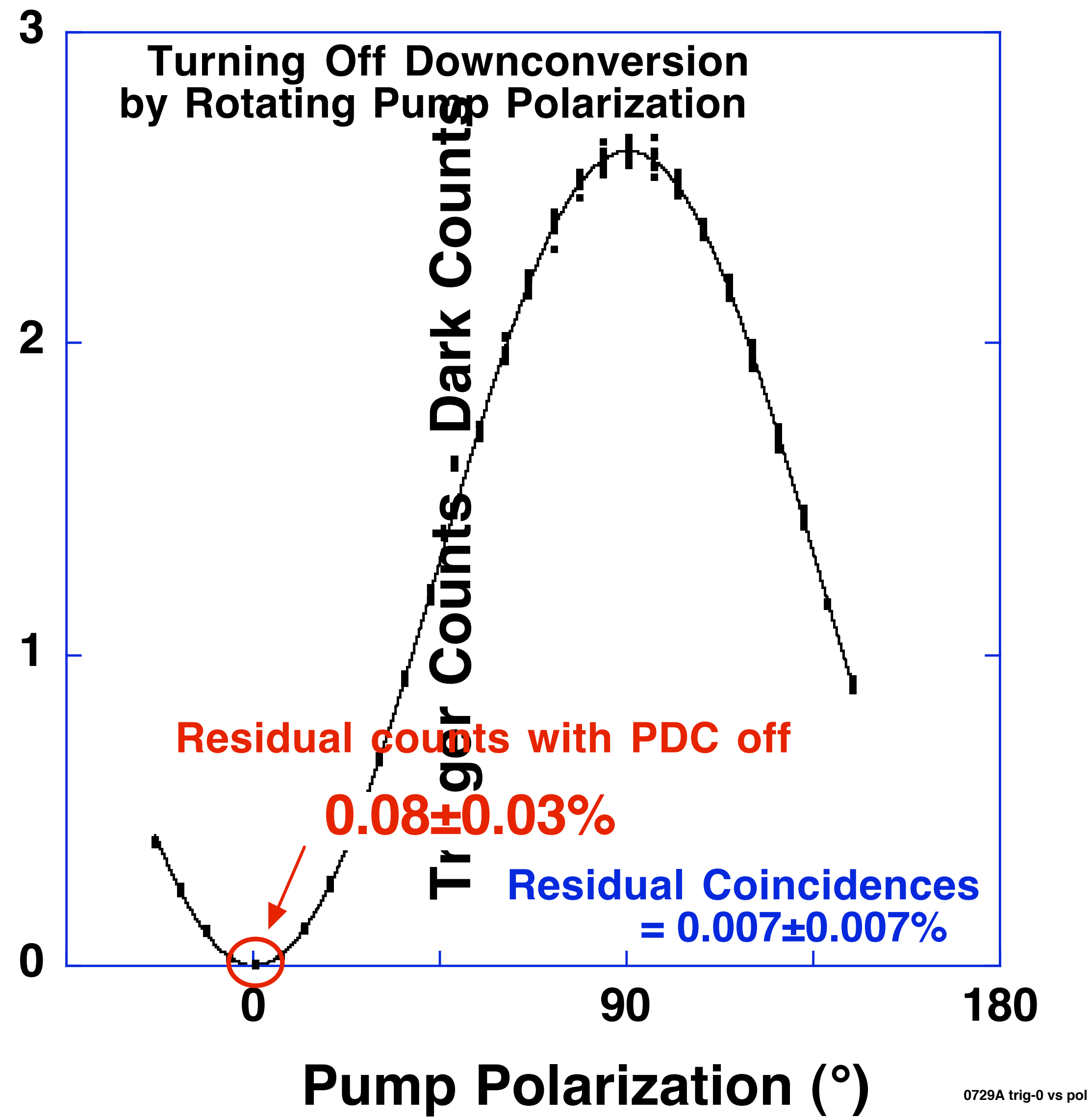
Self Tests-

- Geometric Collection
  - Positioning of detector and collection optics
  - Collection aperture size
- Electronic Collection
  - Map coincidence timing jitter
  - Dark count determination (trigger detector)

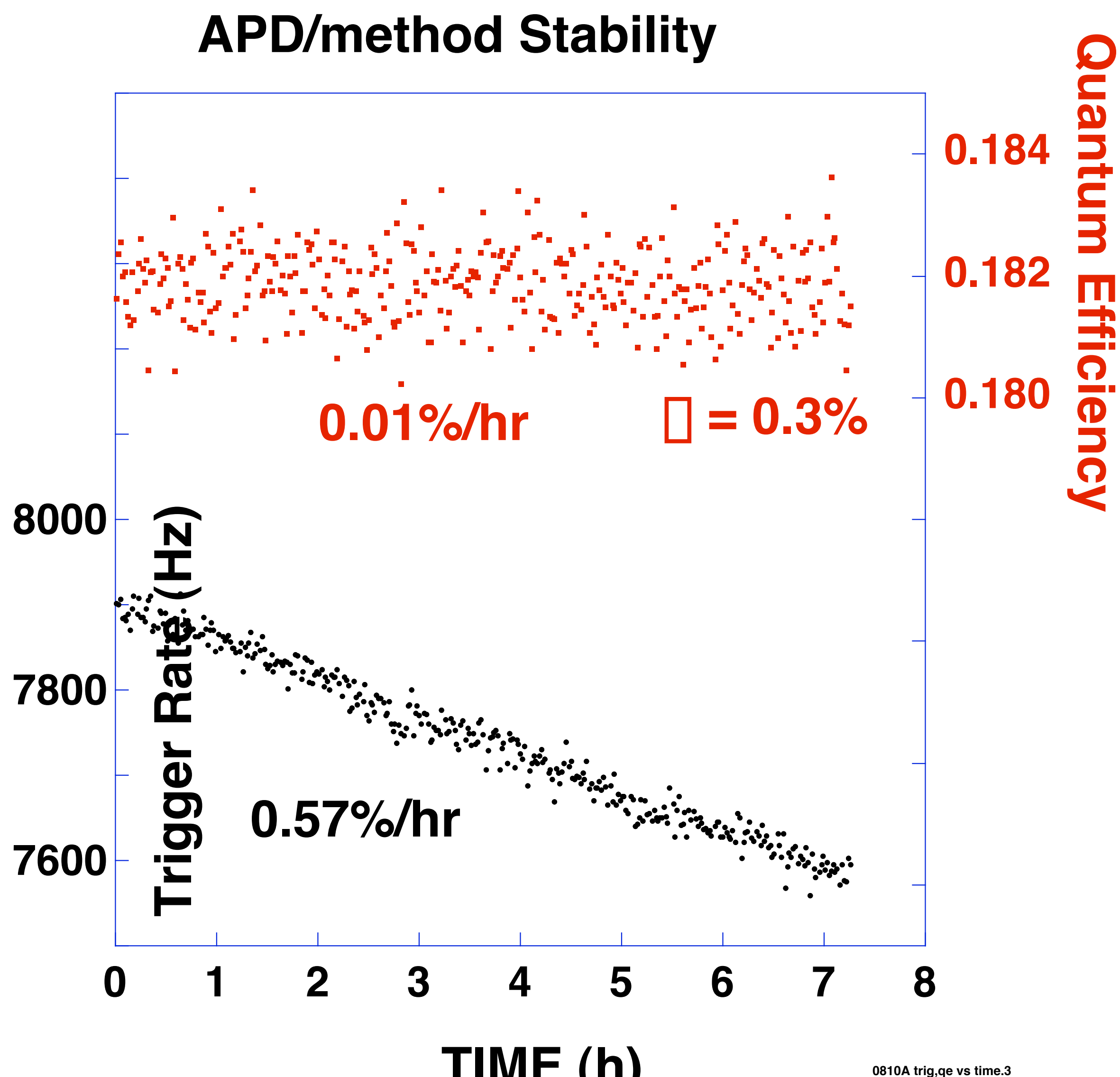
Quantifying Level of Collection Losses



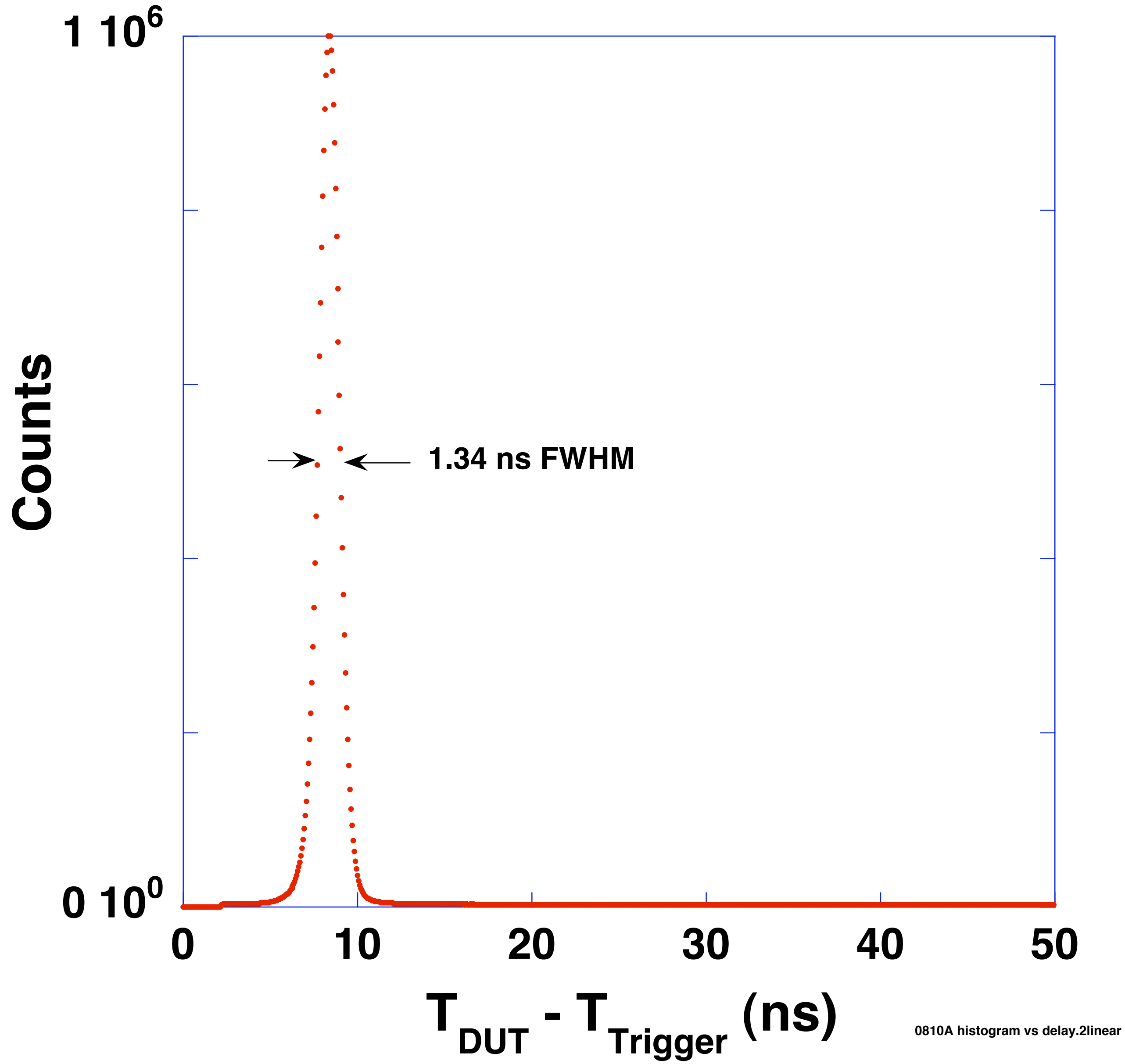
Measuring Unwanted Optical Scatter



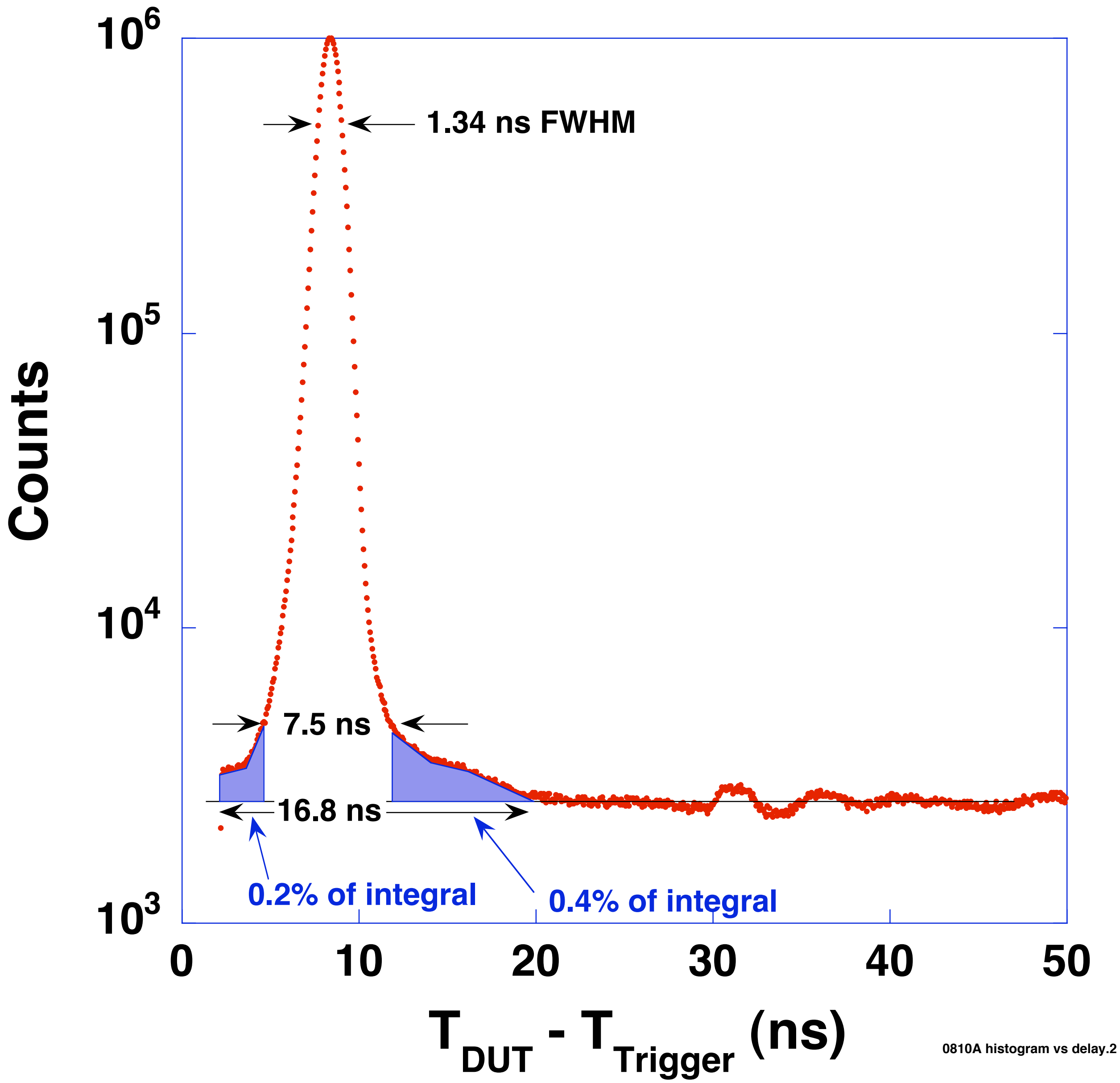
Testing Self-Consistency



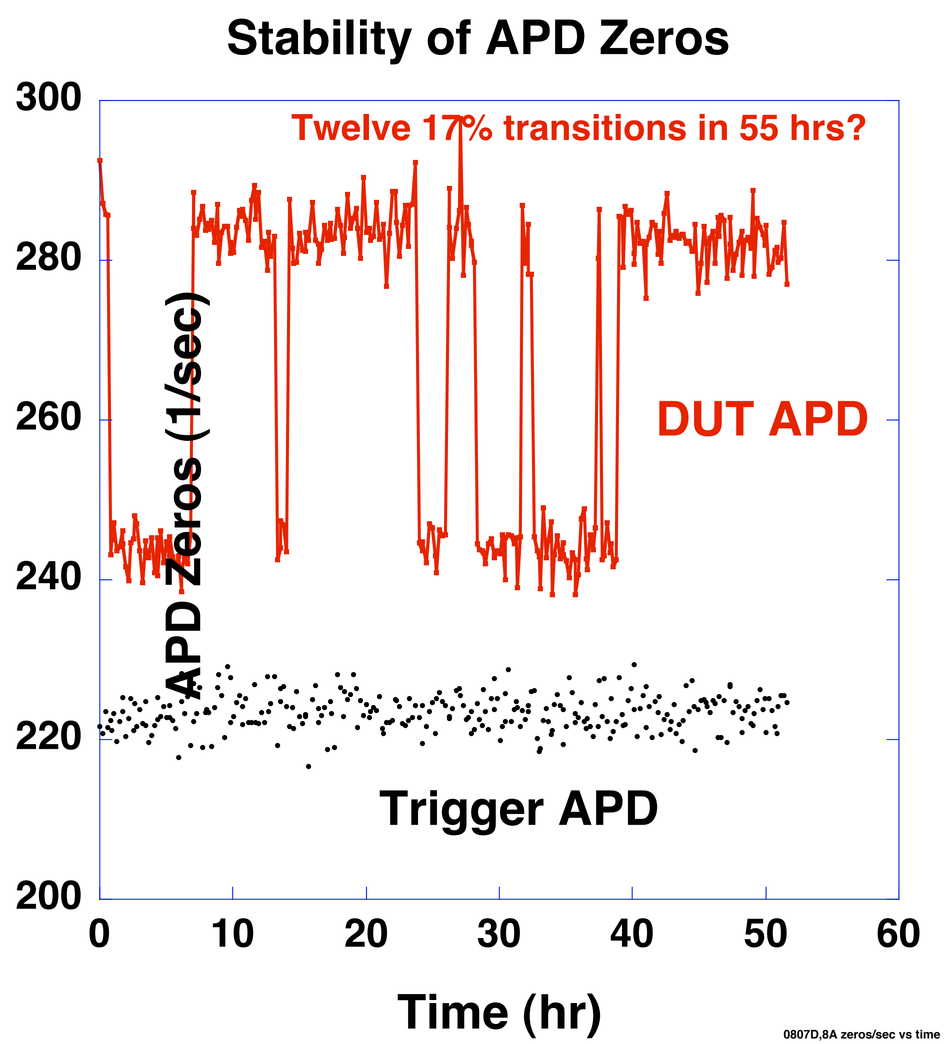
Details of Coincidence Peak



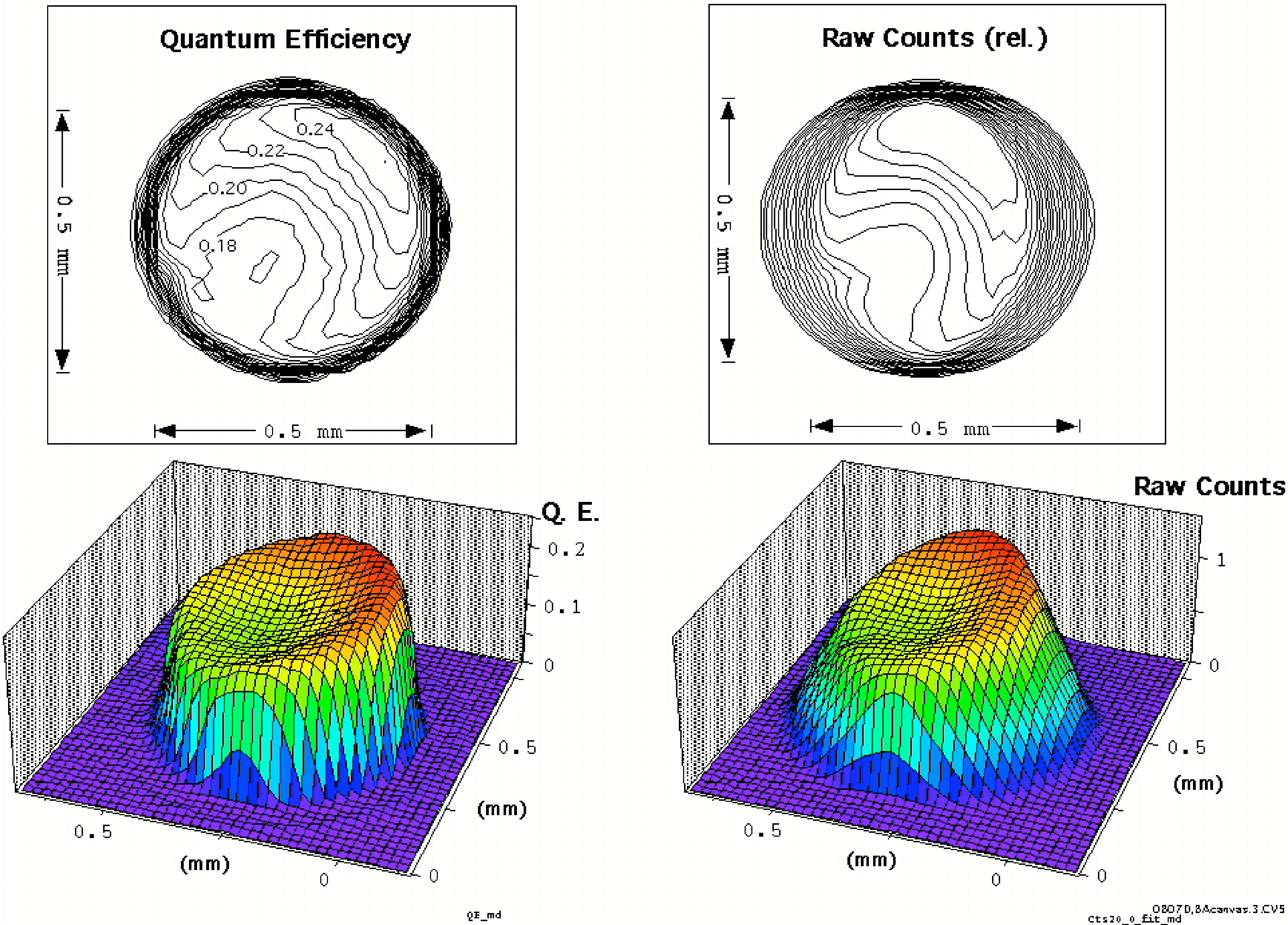
Details of Coincidence Peak



Detector Funny Business



Spatial Maps of Avalanche Photodiode @ 633 nm



Estimated Uncertainties

	value (%)	uncertainty (rel. %)
Inherent in Technique:		
Crystal Transmittance (half)	96.0	0.054
- 1 surface reflectance	4.0	0.02
- internal transmittance	99.95	0.05
Geometric Collection Efficiency	99.8	<0.25
Coincidence Counting	99.9	0.1
Included with DUT:		
Filter transmittance	80.0	0.8
Lens transmittance	99.8	0.04
Detector stability	0.1-0.03	<0.1
Spatial uniformity	50.	0.5 ?

Mainly due to Spectral uncert.

Biggest problem

Values achieved so far

Current tests are limited by DUT uncertainties

Abridged History of Correlated Photon QE Technique: from Demonstrations to Metrology

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1970- First observation of correlation & first detector calibration! - Burnham and Weinberg (NASA)

1977- Proposal for quantum efficiency application??
Proposal for "Optical Brightness Standard" - Klyshko

1981- PMT calibration - Malygin, Penin, Sergienko (Moscow State)

1986- APD calibration - Bowman, Shih, Alley (U of M)
Analog PMT calibration- Sergienko and Penin, (Moscow State)

1987- APD calibration, comparison with conventional methods (~10% uncert.) - Rarity, Ridley, Tapster (Malvern)

1993- SSPM calibration - Kwiat, et al. (UC Berkley)

1993- PMT calibration - Ginzburg, et al., (VNIIFI)

1995- Comparison with conventional methods (<2% uncert.) - Migdall, et al. (NIST)

2002- National metrology labs- Italy, UK, France, Russia, Hungary,….

Now fiber collection matters

(getting down to the business of metrology)

PDC -- single mode fiber collection efficiencies

Collection Efficiencies

Overall		Geometric+
28.6%	39%	Kurtsiefer, et al 2000 (700 nm)
3.1%	18%	Mason, et al 2002, (1600 nm)
9%	26%	our lab (very first results) (920 nm)
22%	63%	our lab (62 μm multimode fiber) (920 nm)

- Thoughts on metrology
- Plans for the future

Philosophy of Measurement Chain

Distance - Spatial

Medium accuracy, local primary standard

vs.

High accuracy, distant primary standard

Distance - Dynamic Range

Existing Detector Standard ~ milliwatt

long attenuation calibration chain to low level calibration

Correlated Photon Method ~ photon counting (<10^{-12} watts)

direct low level calibration

Goal/Vision for NIST's role-

This is a Primary Standard Method

Emphasize *dissemination* of the method

rather than

***Routine* NIST calibration facility**

Keys-

Measurement Protocol

Self consistency tests to verify uncertainties

Intercomparisons

Design aids for Down Conversion Sources

http://physics.nist.gov/Divisions/Div844/facilities/cprad/cprad.html

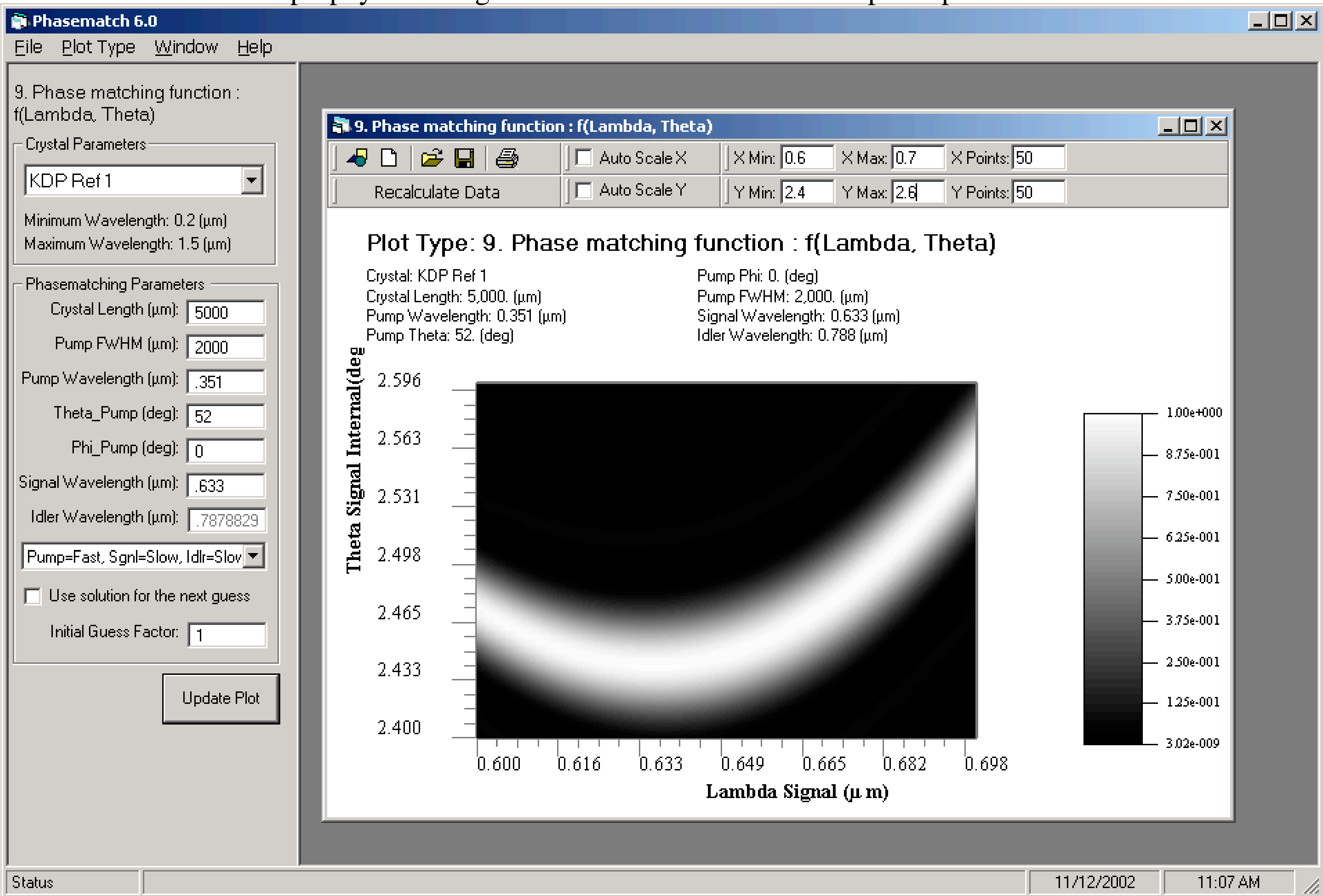
Cost effective measurement systems

e.g. all solid state photon pair source

Volz, Kurtsiefer, & Weinfurter Apl. Phys. Letts. 79, 869(2001)

Noncollinear phasematching software

Http://physics.nist.gov/Divisions/Div844/facilities/cprad/cprad.html



Devices Applications and Methods Single Photon Workshop at NIST

Two-Photon Metrology & Single Photon Industry

- Survey industrial needs – current & future
- Present metrological techniques
- Encourage detector development

Target participants

Users

Manufacturers

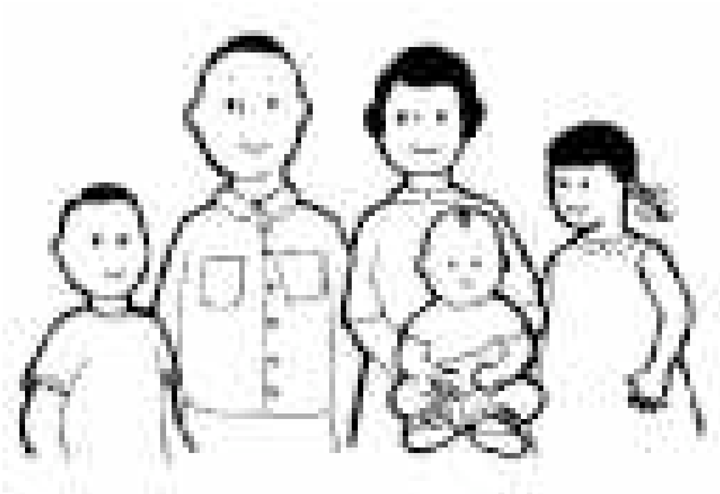
Device researchers & developers

Metrologists

Contact me Alan.Migdall@nist.gov

Heralded Photons & Metrology

- Love at first sight
- An exciting honeymoon
- Numerous children –lots of potential
- Growing to maturity takes lots of work



- Grandchildren ?

The end